In addition, magnetic devices such as transformers, chokes and inductors commonly use silicon grade steel for the magnetic core and copper or aluminum for the windings. Over the last decades, this technology has not progressed but improvements have been made in materials and processes for the constructions of such transformers. However, a need still remains for magnetic technology with reduced energy loss characteristics, reduced weight and lower cost. A need also exists for energy efficient and cost efficient transformers which can be utilized in high power consumption circuits, such as ballasts for street lighting and arc discharge lamp applications, or circuits used in current, power control and distribution.

SUMMARY OF THE INVENTION

It is a feature of the present invention to provide inductor devices which are highly energy efficient and produce low amounts of heat.

It is another feature of the present invention to provide inductor devices which are lightweight and compact.

It is a further feature of the present invention to provide an inductor device which can be used in a variety of different applications, such as a transformer, current controller, or as a power equipment protection device.

According to the above features, from a first broad aspect, the invention comprises an inductor device which includes a magnetic circuit having first and second layers of magnetic conductive material with the layers being retained in a predetermined, spaced-apart relationship with respect to one another, so as to define opposing facing surfaces and at least first and second end portions. The first and second layers further define a gap between the layers. The inductor device further includes a first permanent magnetic piece located at a first end portion between the layers of ferromagnetic material, and a second permanent magnetic piece located at a second end portion between the layers of ferromagnetic

material. A coil surrounds each of the first and second layers of ferromagnetic material with the coil extending within the gap between the first and second permanent magnetic pieces.

According to the above features, from a second broad aspect, the innovation provides a toroidal inductor which has a first semi-circular toroidal ferromagnetic piece having first and second ends and a second semi-circular toroidal ferromagnetic piece having first and second ends. The first and second ends of the first toroidal ferromagnetic piece are arranged to face the first and second ends of the second toroidal ferromagnetic piece such that the ends of the first and second toroidal pieces are opposed and spaced apart. Permanent magnets are interposed between the ends of the toroidal ferromagnetic pieces and are integrally joined with the toroidal pieces. This device further includes a coil surrounding a portion of either the first or second toroidal piece.

According to the above features, from a third broad aspect, the invention provides a multi-phase assembly which includes first and second frames with each of the frames having a perimeter and at least one leg extending within the perimeter of each frame. The first and second frames are retained in juxtaposition with permanent magnets interposed between the first and second juxtaposed frames. A coil surrounds at least a portion of the perimeter and a portion of at least one of the legs.

BRIEF DESCRIPTION OF THE DRAWINGS

The preferred embodiments of the present invention will now be described with reference to the accompanying drawings in which

FIG. 1 illustrates a perspective view of the preferred magnetic core device of the present invention.

FIG. 12 illustrates a hysteresis curve plotting magnetic flux density versus field strength and which further illustrates the static and dynamic operating points of a flux saturated magnetic core device 16 of Fig. 8.

FIG. 13 illustrates an effective hysteresis curve plotting magnetic flux density versus field strength for the combined operation of the two flux saturated magnetic core devices in Fig. 8.

Fig. 14 illustrates hysteresis curves plotting magnetic flux density versus field strength for a standard inductor, choke or transformer, wherein the magnetic core device of the present invention is operated at non-flux saturated conditions.

FIG. 15 illustrates an application of a three-phase transformer in which the operating conditions of Figure 14 are applicable.

FIG. 16 illustrates a vector diagram for showing flux vectors that would be established for an embodiment having reduced hysteresis losses.

FIG. 17 illustrates an alternate embodiment of the invention which utilizes the principles illustrated in FIG. 16.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Figure 1 shows a perspective view of a preferred embodiment of the permanent magnetic core device of the present invention. This device includes two coils 4,5 wrapped around layers of magnetically-conductive steel material 2, forming a ferromagnetic core. Permanent magnetic pieces 3 are placed at opposing ends of the assembly. However, it may be desirable in certain applications to utilize only one magnet in the magnetic core device. To couple the magnetic pieces 3 to the ferromagnetic layers 2, magnetic pole pieces may be utilized in layers positioned between the magnetic pieces 3 and the ferromagnetic layers 2. The magnets 3 are placed in such a manner that their fields are additive. The coils are

Figure 2, "μo" is the permeability of free space and "μr" is the permeability of the ferromagnetic core layers 2.

If a field is applied opposing the magnets by the coils 4 and 5 of Figure 1 of turns N, and current I, then the residual flux density in the magnets will be given by:

(2)
$$Br = \frac{(Npls \cdot Hm \cdot th - N \cdot I) \cdot \mu o}{\left(\frac{H \cdot Lm}{\mu r \cdot Wi}\right) + Npls \cdot th}$$

Since the flux density is the ferromagnetic core is related to the magnetic residual flux density "Br" by the ratio Lm/W, the ferromagnetic core saturation flux density can be approximated by:

(3)
$$Bs = \frac{(Npls \cdot Hm \cdot th - N \cdot I) \cdot \mu o}{\left(\frac{H \cdot Lm}{\mu r \cdot Wi}\right) + Npls \cdot th} \cdot \left(\frac{Lm}{Wi}\right)$$

If the value "Bs" is greater than the value required to saturate the core Bsat. then the inductance of the permanent magnetic core assembly will be minimal. as the current I in coils 4, 5 of Figure 1 is increased to the point where the core desaturates, then the inductance of the permanent magnetic core will maximize. Thus, equation (3) demonstrates that for the saturation mode of the permanent magnetic core device, this device operates as a controller of current. In AC circuits, the maximum inductance value will form a high impedance to current, while the minimal inductance will form a low impedance to current.

<u>Characteristics of Permanent Magnetic Core Device</u>

Figure 5 illustrates the variations of inductance against current on the device of Figure 1 in the magnetic flux saturated condition. As the current changes

technology of the preferred embodiment from Figure 1 (or later described alternate embodiment of Figures 3, 4 and 15) produces energy losses that are much lower than the energy losses experienced by conventional magnetic devices. Such reductions in energy losses translate in a reduction of heat and lower operating costs when the permanent magnetic core devices are utilized in a circuit.

ALTERNATE EMBODIMENTS OF THE INVENTION

Figures 3 and 4 illustrate the alternative embodiments for the permanent magnetic core device. In Figure 3, the permanent magnets 7 are aligned in a plane. Surrounding the magnets are a toroidal ferromagnetic core 6 and pole pieces 8 attached to the internal and external peripheries of the ferromagnetic core 6. A coil 9 is wrapped around the ferromagnetic core 6. Figure 4 illustrates a similar device, although this embodiment does not utilize the pole pieces, and the permanent magnets are shown at 10. In this embodiment, the permanent magnets 10 are shown in parallel planes, which are at an angle to the diametric plane of the toroid. In a further alternate embodiment (not shown) the arrangement of Figure 4 is utilized, but the permanent magnets 10 are arranged in non-parallel planes.

The embodiments of Figures 3 and 4 have been found to be ideal for use as chokes, although their application in specific circuits are not limited to chokes alone. For example, the devices of Figures 3 and 4 may also be utilized as inductors or controllers of current, or transformers.

Another alternate embodiment of the invention is presented in Figure 15. Two core assemblies 21 and 24 are placed adjacent to one another. Magnetic assemblies are composed of magnet sets 19, 20, and pole pieces 25, and these assemblies are then sandwiched between the two core structures 21 and 24. Each of the six magnetic assemblies are arranged to have opposite polarity to each adjacent magnetic assembly in both horizontal and vertical directions. However, magnetic polarity may be varied according to a given application. Each of the three

vertical limbs are enclosed by coils. This particular device is advantageous when used as a power distribution transformer, a power distribution protection device or a current limiting device. The basic theory behind this device has been described according to Figures 5, 6, 7, 11, 12, 13 and 14. An additional discovery has been made in which we have found that if the magnetic field is established in the core which is perpendicular to the magnetic field of the permanent magnets, then the hysteresis curve for such a device will also define a smaller area than what would be observed if the perpendicular magnetic field did not exist. Thus, the creation of a magnetic field in the core which is perpendicular to the field created by horizontal pairs of permanent magnets will result in a device with substantially reduced heat generation, and greater energy efficiency. The transformer device of Figure 15 may be used in three-phase applications and displays the characteristic shown in Figure 6.

As we described the usefulness of static magnetic biasing in reducing core losses in ferromagnetic materials, we have also set out the principle that the bias field may not be restricted to the conventional direction of flux flow, but may also be used in the "orthogonal direction". Our invention can be extended to AC orthogonal biasing in which further advantages are realized in the application of power transformers.

The advantages of magnetic biasing for reducing hysteresis losses have been demonstrated in FIGS 11, 12, 13 and 14, however, we have found that many ferromagnetic materials, including ferrites, can be biased in a multi-dimensional manner as demonstrated in figure 16. Figure 16 illustrates a portion of a ferromagnetic material in which several flux density vectors are imposed. The material will exhibit a maximum flux density vector in the normal direction depicted by the non-linear vector B_norm. Another non-linear flux density vector B_orth may be imposed by a magnet or by a coil, resulting in an overall non-linear flux density vector B_res_O. Although the material may have a magnetic